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# Multimedia Exposure Estimates Applied to Toxic Waste Sites

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# MULTIMEDIA EXPOSURE ESTIMATES APPLIED TO TOXIC WASTE SITES

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Exposure to chemicals which contaminate soils or are buried in land disposal facilities can occur through more than one route. In estimating the magnitude of human intake rates or cleanup levels for contaminated or spill sites, multimedia exposures should be considered. A procedure for estimating simultaneous exposures related to multimedia pathways, including inhalation of vapors, ingestion of contaminated soil, and dermal contact has been developed.

## 1. Introduction

Soil contamination often results from improper land disposal, storage, treatment, and spills of hazardous waste in liquid or solid form. In order to properly address the levels of pollutants to which contaminated soil needs to be cleaned, it is necessary to estimate the magnitude of human exposure for each likely exposure pathway. The procedure developed in this paper for estimating the level of pollutant cleanup from soil relates to 1) identification of exposure pathways, 2) exposure assessment to estimate pollutant intakes by humans from each pathway, and 3) the use of health effects data to estimate the acceptable exposure levels.

Exposure assessment should include short-term and long-term periods of exposure, since acute as well as chronic health consequences need to be considered. Acute effects are normally noncancer effects, while chronic effects can relate to noncancer and oncogenic effects. Depending upon the circumstances under which human exposure occurs and the type of pollutant being considered, exhaustive exposure evaluation for all likely pathways may be avoided, with only the most controlling pathways included in the determination of acceptable contaminant cleanup level in soil.

This paper will present a method intended primarily to allow the estimation of permissible residual levels of contaminant associated with the cleanup of contaminated soils to meet acceptable health effects criteria. It can also be applicable to assessing the limits of pollutant that can be allowed in mixtures of soil and waste being landfilled.

## 2. Exposure Pathways

Contaminants originally present in soil can be distributed in various environmental media. The soil leaching process is a major concern for groundwater contamination. Bioaccumulation in fish, in animals used for food, or in garden vegetables results from contaminated surface water or from contaminated soil on which animals graze or plants are grown. Volatile constituents in soil can be released into the atmosphere because their partial pressure in equilibrium with the concentrations in soil provides the driving force for diffusion along the soil column. Windblown particulate matter can entrain toxic constituents into the air which people breathe. People can work in a garden where there is contaminated soil, and be subjected to dermal contact with pollutants that can be absorbed through the skin.

The presence of contaminants in environmental media being distributed from wastes disposed of in soil thus can pose a potential health risk to humans from the following sources of intake:

- Ingestion of contaminated soil;
- Inhalation of air containing contaminants in vapor or particulate form;
- Absorption of contaminants through the skin because of contact with contaminated soil;

- Drinking of contaminated water; and
- Ingestion of foods with equilibrated or bioaccumulated contaminants.

Other exposure pathways, such as phytotoxicity to plants, may also need to be considered.

Under normal conditions, significant soil ingestion is limited to children (Lepow, 1975). Although very limited information is available on the ranges of age subject to soil ingestion, one investigation presented a case study of an adult with a history of habitual eating of garden soil, which may have been associated with a pica illness (Wedeen et al., 1978). The fraction of soil contaminant absorbed by humans is dependent upon the type of compound and its soil contaminant adsorption characteristics, and is generally smaller than that which can be expected when contaminants are present in food or drinking water.

When exposure locations are distant from the contaminated site, dilution, biodegradation, dispersion, or chemical reactions may have a pronounced effect on exposures. Examples include dilution of contaminants by winds, dispersion in groundwater, and biodegradation in surface water. It is possible to incorporate such processes in exposure evaluations. The significance of exposures to inhaled or dermally-contacted contaminants will also be dependent upon the absorption rate of such contaminants in the lungs or on human skin. The smaller the absorption rate, the less significant the exposure would be.

Once exposure pathways are identified, exposure evaluation requires information on the levels of concentration to which a given target population may be exposed. Each pathway may require route-specific evaluation, as described in the following sections.

## 3. Estimation of Exposures Related to Contaminated Soil

The combined human intake of contaminants from all exposure pathways should not exceed the acceptable intake (AI, in mg/day) needed for preventing adverse effects from short-term and lifetime exposures. Refer to the Nomenclature section for the meaning of symbols used. The intake from an individual route when soil is contaminated can be expressed quantitatively as follows:

### 3.1 Intake by soil ingestion (mg/day):

$$I_1 = (C_s)(IR \times 10^{-3})(GI)(SM)(F) \quad [1]$$

The term $(C_s)(IR)$ in Eq. [1] represents the daily amount of a contaminant ingested resulting from soil ingestion, in µg/day, because $C_s$ represents the contaminant concentration in soil (µg/g) and IR is the soil ingestion rate (g/day). The factor $10^{-3}$ is needed to convert the unit from µg/day to mg/day. The fraction of the ingested contaminants that will enter human organs and systems to cause toxicity is given as GI. If the contaminant undergoes biological or chemical degradation in soil, and follows first-order kinetics in its disappearance under isothermal conditions, the contaminant concentration will change as a function of time according to $C_o e^{-kt}$, where $C_o$ is the initial contaminant concentration in soil. The concentration in soil will also be affected by transport processes, which are incorporated in the individual pathway analysis. An individual may not always be present on the contaminated site over his lifetime. The frequency factor of exposure over a lifetime, SM, represents the fraction of a lifetime that an individual will be exposed to the contaminants under consideration. The factor F is necessary because soil ingestion only occurs during childhood (1 to 6 years of age), and the weight of the human body changes from childhood to adulthood.

### 3.2 Intake by air inhalation of volatilized contaminants (mg/day):

$$I_2 = (K_{as})(C_s)(D)(IH \times 10^3)(ABA)(SM) \quad [2]$$

In Eq. [2], $K_{as}$, D, and IH represent the soil-air partition coefficient, the extent of dilution of the vapor concentration in equilibrium with the contaminant concentration on soil after being dispersed by winds in the atmosphere, and the average daily inhalation rate of ambient air, respectively. The term $(K_{as})(C_s)(D)(10^{-3})$ represents the ambient air concentration of a pollutant at the exposure location in $mg/m^3$ when $K_{as}$ and $C_s$ are given in g soil/$cm^3$ and mg/kg, respectively.

The determination of the ambient air concentration at an exposure location, $(K_{as})(C_s)(D)(10^{-3})$, or the dilution factor in the term, requires the estimation of transient emission rate, and the use of dispersion modeling. The emission rate will not only be transient, but it will also be retarded by soil or equivalent cover material. This phase of the problem requires solution of a partial differential equation, as described below in section 6.

3.3 Intake by dermal absorption (mg/day):

$$I_3 = (C_s)(CR \times 10^{-3})(ABS)(SM) \quad [3]$$

There are many occasions when children playing in the yard or adults working in the garden will come in direct contact with contaminated soil. Dermal contact does not necessarily constitute adverse exposure. The contaminant needs to be systemic to be absorbed into the human body and to exert toxicity. In Eq. [3], the term $(C_s)(CR)$ represents the contaminant contact rate with skin in µg/day since $C_s$ is in µg/g (=ppm) and CR is the dermal contact rate of soil in g/day. The factor $10^{-3}$ is used to convert the contact rate from µg/day to mg/day, and SM will be 1 when the short- or longer-term (10-day) exposure is estimated, and will be between 0 and 1 when the lifetime exposure is estimated.

3.4 Intake by drinking water (mg/day):

$$I_4 = (C_w)(IW)(SM) \quad [4]$$

In Eq. [4] it is assumed that the contaminant in drinking water is completely absorbed into the human body at the average daily water consumption rate of IW or the absorption fraction is 1. In order to relate the contaminant concentration in groundwater, $C_w$, to the contaminant concentration in soil, $C_s$, a fate and transport model can be used to estimate the concentration in the leachate entering groundwater, or

$$C_w = C_L/f_g, \text{ mg/L} \quad [5]$$

where $f_g$ represents a functional relationship describing contaminant transport in groundwater. This function should be selected to suit the most appropriate conditions for the system. The leachate concentration, $C_L$, referring to the contaminant concentration in liquids just before entering groundwater, should not be confused with the contaminant concentration in groundwater, which results from mixing of the leachate with groundwater. Also, care should be exercised in using groundwater transport models, because some models will treat the leachate concentration as a boundary condition, while others require the contaminant concentration in groundwater as a boundary condition, which should be obtained by groundwater monitoring. When the units of $C_w$ and $C_L$ are all in mg/L, then the function $f_g$ becomes dimensionless. Most leachate from hazardous waste land disposal sites may enter groundwater over a finite surface area, favoring area source models for simulating pollutant transport in groundwater.

There is no reliable method of predicting the leachate concentration from the contaminant concentration in soil, or vice versa. For the exposure evaluation, an equilibrium relationship between soil and leachate will provide a first approximation. Monitoring data can also be used relating the concentrations between leachate and soil. An equilibrium condition can be written as

$$C_s = (K_{LS})(C_L), \text{ mg/kg} \quad [6]$$

where $K_{LS}$ is a partition coefficient in (mg/kg)/(mg/L). Eqs. [4], [5], and [6] are combined to get

$$I_4 = \frac{C_s}{(f_g)(K_{LS})}(IW)(SM) \quad [7]$$

When the equilibrium condition is not appropriate, it can be modified to include transport processes between the soil and leachate.

3.5 Intake by fish ingestion (mg/day):

At the average daily fish consumption rate of IF (kg/day), and under the assumption of complete absorption of the contaminant associated with the consumption of fish, the exposure can be estimated as

$$I_5 = (C_F)(IF)(SM) \quad [8]$$

where $C_F$ is the contaminant concentration in fish. The use of the bioconcentration factor BCF, (mg/kg fish)/(mg/L water), to relate pollutant concentrations in fish and water, gives

$$I_5 = (BCF)(C_w)(IF)(SM) \quad [9]$$

where it is assumed that contaminants are present in water in dissolved form and that bottom sediments or benthal deposits on which pollutants may be adsorbed are not directly swallowed by fish. Under the condition of equilibrium between the pollutant-containing soil and leachate which is generated from the soil, substitution of Eqs. [5] and [6] into Eq. [9] results in

$$I_5 = \frac{C_s}{(f_g)(K_{LS})}(BCF)(IF)(SM) \quad [10]$$

The transport functions, $f_g$, in Eqs. [7] and [10] may assume distinct mathematical descriptions, because one pertains to transport in groundwater and the other to that in surface water.

3.6 Intake by inhalation of contaminants adsorbed on particulates (mg/day):

$$I_6 = (C_p)(IH)(C_s \times 10^{-9})(ABP)(SM) \quad [11]$$

Contaminant-containing soil can be airborne by blowing winds. In

addition, toxic substances volatilized from contaminated soil can be adsorbed on particulate matter present in the ambient air. Exposure to contaminants occurs because of inhalation of air containing these particulates. The exposure location could be distant from the source of emission, or in the vicinity of the emission source. Exposure concentrations will change accordingly. Another form of exposure relates to inhalation of air containing particulate matter on which volatile constituents are adsorbed. The intake rate can be estimated based on the concentration of contaminants in wind-dispersed soil or on particulate matter, $C_s$ ug/g (=ppm), and the concentration of the particulates in the ambient air, $C_p$ ug/m$^3$, as shown in Eq. [11]. The absorption fraction, ABP, is used because contaminants present in or on soil (or particulate matter) may be bound on the solid material, reducing the contaminant's absorption rate. Finally, the factor $10^{-9}$ is a conversion factor to make the units consistent.

3.7 Intake by ingestion of vegetables (mg/day):

The intake rate due to ingesting IV kg/day of vegetables, plants, or agricultural products containing $C_v$ mg/L of contaminants will be

$$I_7 = (C_v)(IV)(SM) \qquad [12]$$

If it is assumed that equilibrium is established between the contaminant concentrations in plant and soil, then the exposure can be modified as:

$$I_7 = (K_{sv})(C_s)(IV)(SM) \qquad [13]$$

where $K_{sv}$ is a partition coefficient defined as contaminant concentration in plant/total contaminant concentration in soil (mg/kg plant)/(mg/kg soil).

3.8 Intake by ingestion of food meat:

The contaminant intake at consumption rate of IM (kg/day) of meat containing $C_m$ (mg/kg) of pollutant is

$$I_8 = (C_m)(IM)(SM) \qquad [14]$$

Here again, an equilibrium relationship is assumed between the contaminant concentrations in the animal body and plants. Therefore, the intake rate due to meat consumption is

$$I_8 = (K_{vm})(C_v)(IM)(SM)$$

$$= (K_{vm})(K_{sv})(C_s)(IM)(SM) \qquad [15]$$

where $K_{vm}$ and $K_{sv}$ are the partition coefficients used to describe pollutant distribution between meat and vegetables, and the partition between vegetables and soil, respectively.

Similar expressions can be written for other routes of exposure. In Eq. [4], it is assumed that the groundwater concentration of a pollutant at an exposure location can be determined (by using monitoring data or fate and transport models) from the knowledge of leachate concentration as given by a function $f_g$, and that the contaminated soil and its leachate are in equilibrium as given by $K_{LS} = C_s/C_L$. There are a number of functional relationships which can be used in place of $f_g$, as reviewed by Hwang (1984). Also, equilibrium relationships are assumed between fish and water for bioaccumulation, between soil and vegetables, and between food animals and plants consumed by the animals. In Eqs. [7], [10], [13], and [15], contaminants consumed by humans because they are present in drinking water, fish, and other food sources, are taken as completely absorbed by the human body. If data on the absorption rate for these pathways are available, such data should be used.

## 4. Determination of Permissible Pollutant Level in Soil

The total intake from all possible exposure pathways is set equal to the acceptable intake (AI) for short-term and chronic health effects; or

$$AI = I_1 + I_2 + I_3 + \cdots \qquad [16]$$

Eq. [16] can be solved for permissible contaminant levels in soil corresponding to each acceptable intake. It is possible that some exposure pathways occur independently of others. For example, a residence which is located on a contaminated site may use drinking water from a clean public water treatment system, and may thus be free of contaminants found on the site. It is also possible that domestic animals are not raised for food consumption on the contaminated site under consideration. Under such circumstances, all exposure pathways need not be considered. If exposure pathways of significant concern are related to soil ingestion, inhalation of contaminated air, or dermal contact with soil, Eqs. [1], [2], and [3] can be added to solve for $C_s$,

$$C_s = (AI)(1000)/[(IR)(GI)(F) +$$

$$(K_{as})(D)(IH)(ABA \times 10^6) + (CR)(ABS)]SM \qquad [17]$$

The emission rate is limited by the air phase concentration in equilibrium with the contaminant concentration in soil. Once the contaminant soil concentration reaches the level at which the vapor phase concentration

in equilibrium with the soil is at the vapor pressure concentration, a further increase in contaminant concentration in soil ($C_s > C_{sm}$) does not increase the emission rate. At or above this concentration, the ambient air concentration remains constant regardless of the concentration of the contaminant in soil. Under such conditions, $C_s$ in Eq. [2] is no longer a variable, and therefore Eq. [17] does not apply. This situation can be remedied by considering the intakes by the individual route of exposure at a constant value of $C_s$ ($C_s = C_{sm}$ in Eq. [2]) for inhalation exposure, and solving for $C_s$. The form of the equation will be slightly different from that for Eq. [17].

$$C_s = (AI)(1000) - (K_{as})(C_{sm})(D)(IH \times 10^3)\ (ABA)(SM)/ [(IR)(GI)(F) + (CR)(ABS)]SM \quad [18]$$

## 5. Incorporation of Time-varying Parameters

The body weight of a human constantly changes until maturity. The calculation of AIs from the safe dose level (SL) given in mg/kg·day requires requires an assumption of body weight. For rigorous treatment, the estimation of lifetime exposure should take into account changes in body weight. In this case, it is convenient to work with SL instead of AI for exposure calculations. For carcinogens with a potency value at POT $(mg/kg \cdot day)^{-1}$, the equivalent SL at an assumed risk level, R (such as $10^{-6}$, etc.), can be obtained by

$$(SL)eq. = \frac{R}{POT}\ , mg/kg \cdot day$$

The risk level shown represents an upper-bound estimate. An upper-bound estimate of risk of $10^{-6}$, for example, means that upon lifetime exposure to a contaminant, a person experiences an increased maximum risk of developing cancer in a probability of 1 in one million.

Snyder (1975) presented data on the change of body weight as a function of age. A regression analysis on Snyder's data for average male weight provides the following relationship.

$$BW = 3.14 + 3.52\ (age),\ kg \quad \text{for age 0 - 18 yr} \quad [19]$$

$$BW = 70,\ kg \quad \text{for age greater than 18 yr} \quad [20]$$

To obtain the daily exposure averaged over an individual's lifetime, intake rates given by Eqs. [1] - [3], [7], [10], [11], [13], and [15] should be divided by the body weight, and the daily intake per unit body weight should be averaged by summing the total intake per unit body weight over the period during which exposure occurs and dividing the result by LT.

## 6. Inhalation of Volatilized Contaminants

Exposure occurs at or near contaminated sites through inhalation of ambient air contaminated with toxic vapors or particulate matter on which a contaminant is absorbed. Volatile constitutents emitted from contaminated soil will be diluted by the action of winds before a person inhales the ambient air. When a contaminant is adsorbed on soil, the vapor pressure of the contaminant above the soil surface will be always smaller than the pure component vapor pressure. In other words, the adsorption phenomenon depresses the vapor pressure that can exist under saturated conditions. When adsorption reaches its saturation capacity on soil, the partial pressure will be equal to the pure component vapor pressure.

In calculating ambient air concentrations of contaminants, the first task is to estimate emission rates from the bulk of soil contaminated at various concentrations. The emission rate calculations for steady-state conditions can be performed using the methods presented by Farmer et al. (1980), and subsequently summarized by Hwang (1982). Thibodeaux and Hwang (1982) presented the transient emission rate from land treated facilities. A new mathematical treatment is needed to estimate transient rates of emissions from contaminated soil. The transient emission rate is obtained by solving a partial differential equation based on a material balance around the soil column. The solution of such an equation for use in estimating the average emission rate of a non-instantaneous contaminant occurring over an exposure time was presented by Hwang and Falco (U.S. EPA, 1986).

Dispersion models (Bruce, 1969; Wark and Warner, 1981) estimate the ambient air concentrations to which populations may be exposed on a daily or annual basis. While these dispersion models can be used, at any distance x from the site, to estimate ambient air concentrations, they cannot be used on-site. On-site ambient air concentrations can be estimated using the following equation:

$$C_a = \frac{Q}{(LS)(V)(MH)} \qquad [21]$$

The dilution factor needed in using Eq. [2] or [17] can be obtained by:

$$D = C_a/C_{as} \qquad [22]$$

The value of $C_{as}$ increases continuously as the contaminant concentration in soil increases, until the concentration of contaminant in the air phase corresponds to that of contaminant vapor pressure. Once the condition of vapor saturation is reached, a further increase in contaminant concentration in soil will have a minimal effect on the volatilization rate.

## 7. A Case Study for PCBs Cleanup Levels

The method described above is applied to develop advisory levels for polychlorinated biphenyls cleanup, in order to protect public health from short-term and long-term exposures. Exposure pathways considered in developing the advisories include drinking water, ingestion of PCB-contaminated soil by children and adults, inhalation of ambient air, and dermal contact. Other exposure routes, such as food intake and ingestion of fish which have bioaccumulated PCBs, are considered to the extent that these pathways constitute relatively important exposure routes.

In view of the high bioaccumulation factor for PCBs, the consideration of bioaccumulation is important in setting permissible PCB levels in surface water in which aquatic animals live, or its bottom sediments. If one of these routes is a controlling factor in relation to the exposure route or human intake considered, the advisory levels presented here need to be re-evaluated. The example shown here uses the values for pertinent exposure parameters as presented in Table 1.

For lifetime exposure, the permissible PCB concentrations in soil for each carcinogenic risk level from $10^{-5}$ to $10^{-7}$ are based on the potency factor of 4 $(mg/kg \cdot day)^{-1}$, rounded off from two separate evaluations reported for PCB-1260. The permissible levels for short-term exposure can be similarly derived, once the acceptable intake rate is available.

## 8. Example Calculations

### 8.1 Unsteady-state emission rate from contaminated soil with no cover

In this example, soil contaminated with PCB-1254 is assumed to be exposed to the atmosphere in the absence of a cover. The average emission rate, which is obtained by averaging the instantaneous emission rate over a time period, t (sec), can be calculated as follows (refer to U.S. EPA, 1986 for detailed equations): For $D_i = 0.05\ cm^2/s$, $\varepsilon = 0.35$, and $K_d = 1000\ cm^3$ water/g soil:

$$D_{ei} = 0.05\ (0.35)^{1/3} = 0.0352\ cm^2/s$$

$$\frac{H}{K_d} \text{ in } \frac{g\ soil}{cm^3\ air} = \frac{8.37 \times 10^{-3}}{1000} \times 41$$

$$= 0.000343\ \frac{mg/cm^3\ air}{mg/g\ soil}$$

Hence,

$$\alpha = \frac{0.023}{0.35 + 2.65(0.65)\ \frac{1}{0.000343}}$$

$$= 2.45 \times 10^{-6}\ cm^2/s$$

The average emission rate when the initial concentration in soil is $C_{SO} = 10^{-6}$ g/g (= 1 ppm), can be obtained by averaging over 70 years:

- 70 years (= $2.2075 \times 10^9$ sec) average:

$$\bar{N}_A = 0.00034(0.35)\ \frac{2(0.0352)(10^{-6})}{3.14(2.45\times10^{-6})(2.2075\times10^{9})}$$

Table 1. Parameter Values Used in Exposure Evaluation

| | | |
|---|---|---|
| Body weight[a]: | Adult | 70 kg |
| | Child | 10 kg |
| Lifetime: | | 70 years |
| Soil ingestion rate: | | 3 g/day with pica, ages 1-6 |
| | | 0.6 g/day without pica, ages 1-6 |
| Dermal contact rate of soil: | | 1 g/day |
| Daily consumption rate: | | |
| Fish | | 0.0065 kg/day |
| Vegetables | | 0.01 kg/day |
| Meat | | 0.63 kg/day |
| Air inhalation rate: | Adult | 20 $m^3$/day |
| | Child | 10 $m^3$/day |
| Water ingestion rate: | Adult | 2 L/day |
| | Child | 1 L/day |

[a]Average values.

$$= 6.4 \times 10^{-14} \text{ g/cm}^2\text{-s}$$

Although the cleanup level is initially unknown, solution of Eq. [2] or [17] for $C_s$ does not require trial and error calculations, because the dilution factor can be calculated independent of the contaminant concentration in soil in the absence of a cover material.

8.2 An example of the air dilution factor calculation

This example illustrates the method of calculating the air dilution factor needed in the exposure analysis. The emission rates are used as input in applying dispersion modeling to obtain the ambient air concentration, $C_a$, downstream of the site. An average wind speed of 10 mph (=4.47 m/s) is used in this exposure evaluation. The on-site ambient air concentration is calculated using Eq. [21]. For the 70-year average emission rate without cover, calculated above, the on-site air concentration for a 0.5-acre site can be obtained as follows:

$$C_a = \frac{6.4\times10^{-14}\times10^{6}(0.5)(4.047\times10^{7})}{45(4.47)(0.5)(2)}$$

$$= 6.4 \times 10^{-3} \text{ µg/m}^3$$

The vapor phase concentration of PCB being emitted from the soil surface is assumed to be in equilibrium with the assumed soil PCB concentration (1 ppm = 1 µg/g). This vapor phase concentration, before being mixed with air, is:

$$C_{as} = \frac{H}{K_d}(41)\,C_s =$$

$$0.000343 \text{ g soil/cm}^3\cdot(10^6\text{cm}^3/\text{m}^3)\cdot 1 \text{ µg/g}$$

$$= 343 \text{ µg/m}^3$$

Hence, the dilution factor, D, for the on-site ambient air becomes

$$D = 6.4 \times 10^{-3}/343 = 1.87 \times 10^{-5}$$

The concentration of PCBs in soil corresponding to the saturation point can be estimated from the knowledge of vapor pressure and air-soil partitioning. For example, since the vapor pressure of Aroclor-1254 ($7.71 \times 10^{-5}$ mmHg) corresponds to the saturation concentration, $C_{as}$, of 1,372.7 µg/m$^3$, the PCB concentration in soil at the saturation point is:

$$C_{sm} = \frac{1{,}362.7 \text{ µg/m}^3}{[K_{as}(\text{g soil/cm}^3 \text{ air}) \times 10^6 \text{ cm}^3/\text{m}^3]}$$

$$= 1{,}362.7/(0.000343\times10^6) = 4 \text{ µg/g}$$

for a value for $K_d$ of 1,000 cm$^3$/g used in this example. The saturation concentration is dependent upon the value of the air-soil partition coefficient. The concentration of PCBs in saturated vapor and the corresponding PCB concentrations in soil are calculated for $K_d$=1000 and 40 cm$^3$/g. Table 2 lists the calculated values. Since the PCB concentration in vapor phase cannot exceed the saturation concentration, the values of $C_s$ in Eq. [2] or [17] cannot exceed the maximum value, $C_{sm}$.

Table 2. Concentration of PCBs in Soil at Saturation Vapor Pressure at Two $K_d$ Values

| | PCB soil concentration in equil. with saturated vapor (ppm) | | Saturated vapor concentration (µg/m$^3$) |
|---|---|---|---|
| | K =1000 | K =40 | |
| Aroclor-1242 | 250 | 10 | 5823.3 |
| Aroclor-1248 | 55.3 | 2.2 | 7962.8 |
| Aroclor-1254 | 4 | 0.16 | 1362.7 |
| Aroclor-1260 | 28.2 | 1.13 | 822.8 |

## 9. Results of Example Calculations

For exposure pathways by soil ingestion, vapor inhalation, and dermal contact with soil, Eq. (17) is applied to solve for $C_s$ corresponding to the lifetime cancer risk dose at $10^{-6}$ risk:

$$C_s = 1.75 \times 10^{-5} \times 1000/[0.6(0.3)(0.323)$$

$$+ 0.000343(1.87\times10^{-5})(20)(0.5)(10^6)$$

$$+ (1)(0.05)]0.5$$

$$= 0.2 \text{ ppm}$$

This value of $C_s$ should be reused to calculate a new value for $C_s$, which is also found to be 0.2 ppm. In these calculations, it is assumed that GI = 0.3, ABA = 0.5, ABS = 0.05, and SM = 0.5. For short-term exposure calculations, the value for SM = 1 can be assumed, meaning that the frequency of presence on-site for a given day is 1.

When all four Aroclors and the upper and lower values of $K_d$ (1000 and 40) are considered, the permissible levels can be summarized as ranges within which a permissible level of PCB cleanup should lie. These ranges reflect the different Henry's Law con-

stant for each Aroclor in addition to the water-soil partition coefficient, and are shown in Table 3. The symbol, VS, indicates that the emission occurs at vapor saturation conditions, and hence no upper bound limit of PCB concentration for inhalation exposure can be determined. It is assumed that at a distance of 0.1 km from the site, the exposure occurs through inhalation only. Similar calculations were performed under the scenario that the site is covered with clean soil material or its equivalent after cleanup.

Table 3. Levels of Evaluated PCBs in Soil Corresponding to AIs with no Cover (PPM)

| | Lifetime intake level | | |
|---|---|---|---|
| | 0.00175 | 0.0175 | 0.175 |
| | ($10^{-7}$ risk) | ($10^{-6}$ risk) | ($10^{-5}$ risk) |
| Soil ingestion[a] Dermal contact Inhalation | 0.008-0.01 | 0.08-0.1 | 0.8-2 |
| Soil ingestion[b] Dermal contact Inhalation | 0.01-0.06 | 0.1-0.6 | 1-6 |
| On-site inhalation only | 0.01-0.2 | 0.1-2.0 | 1-20 |
| 0.1 km from site | 2-220 | 90-VS | VS |

[a]Children ages 1-6, with pica, consuming 3 g soil/day.
[b]Children ages 1-6, without pica, consuming 0.6 g soil/day.

## 10. Discussion

Except for the calculations pertaining to estimation of emission rate and dispersion modeling, the method presented is straightforward in estimating multimedia exposures for use in determining cleanup levels of contaminants in soil.

There are uncertainties associated with input parameters in estimating exposures. Although the ranges of values for permissible cleanup levels have been obtained for PCB examples without defining uncertainty limits, site-specific evaluations can narrow the confidence intervals.

Recent experimental investigations show that the capillary effect may play a role in controlling the volatile emission rate when cover material is applied (DuPont, 1985). The data indicate that, for certain land-spread chemicals, the emission rate increases rather than decreases as time elapses, as predicted by solving for Fick's law of diffusion. The liquid waste initially spread on land and covered by soil will exert capillary tension in the dry zone of cover material, and will slowly rise toward the soil surface. This is suspected to be the cause of the increasing emission rate at a longer elapsed time than at the beginning of the initial coverup. The increased emission will have an effect on lowering permissible levels of contaminants in soil when inhalation exposures are significant. The degree of liquid saturation to produce this "wicking" effect, if any, is unknown.

## 11. Nomenclature

A = Cross-sectional area of interest in soil column, $cm^2$

ABA = Absorption factor for inhaled contaminant

ABP = Absorption factor for a contaminant on particulate matter being inhaled

ABS = Absorption factor for dermally contacted contaminant

AI = Acceptable intake, mg/day

BCF = Bioconcentration factor, L/kg

BW = Body weight, kg

C = Concentration of a contaminant in the vapor phase in soil pores, $\mu g/m^3$

$C_a$ = Ambient air concentration at exposure location, $\mu g/m^3$

$C_{as}$ = Contaminant concentration in air at the soil surface where emission occurs, $\mu g/m^3$

$C_F$ = Concentration of contaminant in fish, mg/kg

$C_L$ = Concentration of contaminant in leachate, mg/L

$C_m$ = Concentration of pollutant in meat, mg/kg

$C_o$ = Initial concentration of contaminant in soil, mg/kg

$C_p$ = Concentration of contaminant in particulates being inhaled, $\mu g/m^3$

CR = Dermal contact rate of soil, g/day

$C_s$ = Concentration of contaminant in soil, mg/kg [=$\mu g/g$]

$C_{sm}$ = Contaminant concentration in soil corresponding to vapor saturation, mg/kg [=ppm]

$C_w$ = Concentration of contaminant in water, mg/L

$D_{ei}$ = Effective diffusivity, $cm^2/s$ ($=D_i \varepsilon^{1/3}$)

$D_i$ = Molecular diffusivity, $cm^2/s$

D = Air dilution factor ($=C_s/C_{as}$)

F = Correction factor for changing body weight when AI is based on 70 kg BW and soil ingestion lasts only during childhood as compared to lifetime; for soil ingestion during ages 1 through 5, F = 0.323

$f_g$ = Functional relationship defining fate and transport of contaminants in leachate to groundwater

GI = Absorption rate in gastrointestinal tract

H = Henry's Law constant, $atm \cdot m^3/mol$

IH = Daily inhalation of air, $m^3/day$

IF = Daily fish consumption, kg/day

IM = Daily meat consumption, kg/day

IV = Daily vegetable consumption, kg/day

IW = Daily water consumption, L/day

IR = Daily ingestion rate of soil, g/day

k = Biodegradation constant, L/day

$K_{as}$ = Soil-air partition coefficient, g soil/$cm^3$ air [$=41H/K_d$]

$K_d$ = Soil-water partition coefficient, $cm^3$ water/g soil

$K_{LS} = C_s/C_L$

$K_{sv} = C_v/C_s$

$K_{vm} = C_m/C_v$

LS = Width dimension of contaminated area perpendicular to wind direction

LT = Exposure time over a lifetime, 70 years (days)

MH = Mixing height, m

$N_A$ = Emission rate, $\mu g/cm^2 \cdot s$

$\overline{N}_A$ = Average emission rate, $\mu g/cm^2 \cdot s$

POT = Potency slope factor, $(mg/kg \cdot day)^{-1}$

Q = Total emission rate, $\mu g/s$

SL = Safe levels for noncancer effects, mg/kg·day

SH = Exposure frequency over a lifetime

t = Time, s

z = Depth measured from the soil-air interface, cm

V = Average wind speed within mixing zone = (0.5) wind speed at the mixing height, m/s

Greek Letters

$\varepsilon$ = Porosity

$\bar{\rho}_s$ = Bulk density of soil, $g/cm^3$

$\rho_s$ = True density of soil, $g/cm^3$

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